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High-Efficiency Longitudinal Diode Bar Pumping of Solid-State Lasers

15 March 1994

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Abstract

A longitudinal diode bar pumping scheme for a solid state laser has been conceived which can concentrate tens of watts of pump power into a 250 μm spot with nearly 100% efficiency.

Introduction

For many years longitudinal pumping of lasers has proven to be an effective method for maximizing the conversion of pump photons to laser photons. Sipes [1] demonstrated that a collimated phase coupled diode laser array could be axially focused into a Nd:YAG crystal to yield an overall efficient device. At higher diode pump powers (1 watt) this approach was shown to give consistently better than 60% optical conversion efficiency for $Nd^{3+}(^4F_{3/2} \rightarrow {}^4I_{11/2})$ lasing [2]. As one method to reach still higher powers and retain efficiency, Fan et al. [3] showed that several diode lasers, similar to those used by Sipes, could be separately collimated and simultaneously focused by a single large aperture lens to one spot within the laser mode. Because of cost and practicality issues, most higher power diode pumped lasers have been pumped by diode laser bars. Attempts to efficiently collimate diode bars containing groups of phase coupled arrays (or large area stripes) have been limited due to the complex wavefront of the emitters.

The concept presented here is based on the implementation of a new diode bar containing uncoupled index guided single transverse mode diode lasers with a matching microlens array. The end result is efficient (nearly 100%) collection and collimation of the diode bar laser light. We have developed a stand-alone array of microlenses which are spaced on the identical centers as the individual single mode lasers so that the output of each element of the bar is collimated. The important distinction between the present technique and the other efforts alluded to above is that the emission of each diode laser element can be collimated by a single optic since the wavefront is nearly planar. The more traditional gain guided wide stripes or phase coupled arrays typically require separate axis collimation to reach diffraction limited far field images. The present approach stresses the ultimate packing density of single mode lasers in a bar format and fabrication techniques for high quality microoptics.

Results

To test the bar-microlens array concept, an array of microlenses was designed to match the divergence properties of the Spectra Diode Labs 5410 single mode laser. This laser has approximately a 3:1 out-of-plane: in-plane aspect ratio and a divergence of ~ 900 mrad ($1/e^2$ full angle) in the former direction. Because only one-third of a lens would be illuminated along the array axis, the lenses were configured to overlap by one-third with each other to maximize the packing density (see Fig. 1) and ultimately the power per collimated bar. Clearly, the diode elements could be increased in power or more closely spaced. However, the diode spacing is limited by the effective potential for cross coupling between elements. Furthermore, if the element spacing is increased, the microlens diameter can be increased, thereby relaxing the diode-to-lens registration tolerance. At present, the SDL-5410 produces reliable output up to 100 mW. The design which follows below effectively combines all the above design criteria.

Liau et al. [4] recently demonstrated microlens technology with InP and GaP, whereby a wedding cake-like structure could be smoothed into a lens via

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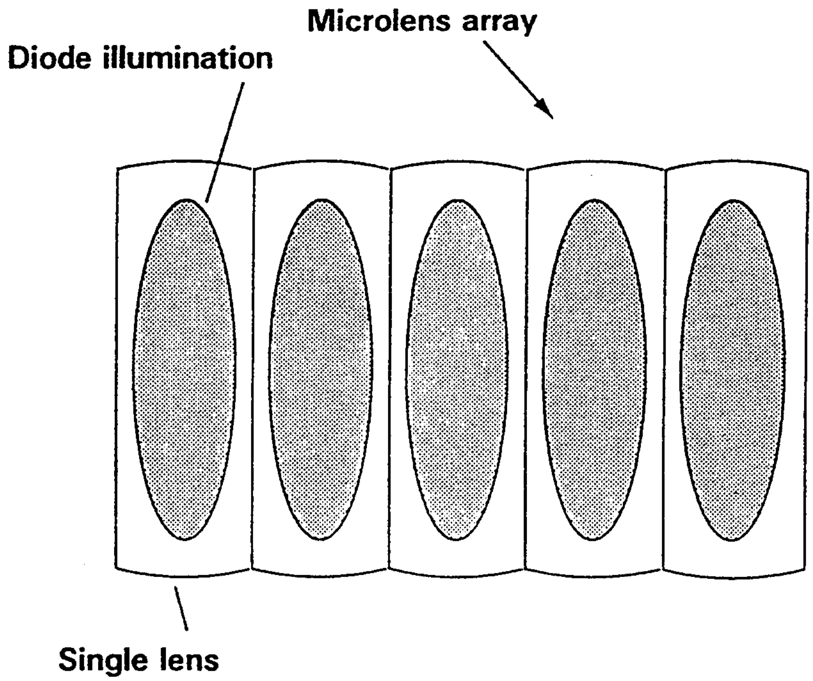

Figure 1. Illustration of adjacent lenses in array and illumination by diode bar.

mass transport. To improve lens repeatability and accuracy, the wedding cake layers on GaP were formed by ion milling as opposed to chemical etching. Additionally, the lens size and finish were enhanced by the development of a novel encapsulation approach for the mass transfer process. Using the above techniques we have fabricated 150 μm fl hyperbolic lenses (160 μm diameter) on 200, 100 and 50 μm centers and 300 μm fl (300 μm diameter) hyperbolic lenses on 100 and 500 μm centers. A photograph of our 300 μm lens array chosen for the ultimate bar collimation is shown in Fig. 2. One single mode diode laser (SDL-5410) was used to test the optical integrity of this microlens array. The 5410 optical divergence was measured to be 28.8° and 6.6° FWHM in the vertical and horizontal directions respectively. After correcting for the fresnel losses nearly 100% of the light from the microlens collimated 5410 was collected in a single uniform spot (see Fig. 3). This result demonstrates that there is minimal distortion caused by the boundary points between the overlapping lenses. The subsequent vertical and horizontal divergences were 3.0 and 11.7 mrad, which are 1.2 and 1.1 times the respective diffraction limits. This assumes that the diode is a pure gaussian output and attributes the small imperfection of the beam to the lens.

To date, several efforts have been performed to antireflection coat the GaP lenses. R. Waarts of Spectra Diode Labs has coated GaP for 950 nm with Al_2O_3 and achieved 98% transmission [5]. Our best effort has been 94% transmission at 808 nm with aluminum oxide. Efforts are currently being pursued to get a better index match to the GaP at 808 nm for higher transmission.

The successful collimation of the single diode device suggests that a 1 cm diode bar can be fashioned with an array of 100 single mode 5410-like 100 mW devices spaced on 100 μm centers to yield a 10 watt collimated device. When such a device is configured as shown in Fig. 4, a 2.1 cm fl focusing lens should theoretically yield a focused spot about 80 by 240 μm. Our tests with the single laser diode, microlens, and focusing lens results in transmission through 100, 200, and 500 μm apertures of 0.8, 0.9, and 1.0, respectively. A diode bar fitting the above specifications is currently being fabricated.

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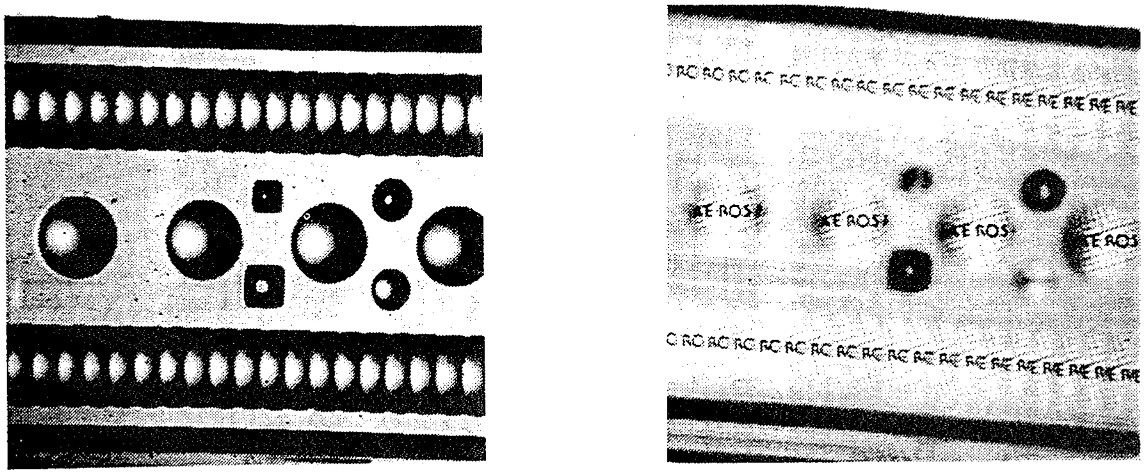

(a) (b)

Figure 2. Photograph of sample 300 μm diameter GaP lenses on 100 and 500 μm centers: (a) focused on the microlenses, (b) focused on the images formed above the microlenses.

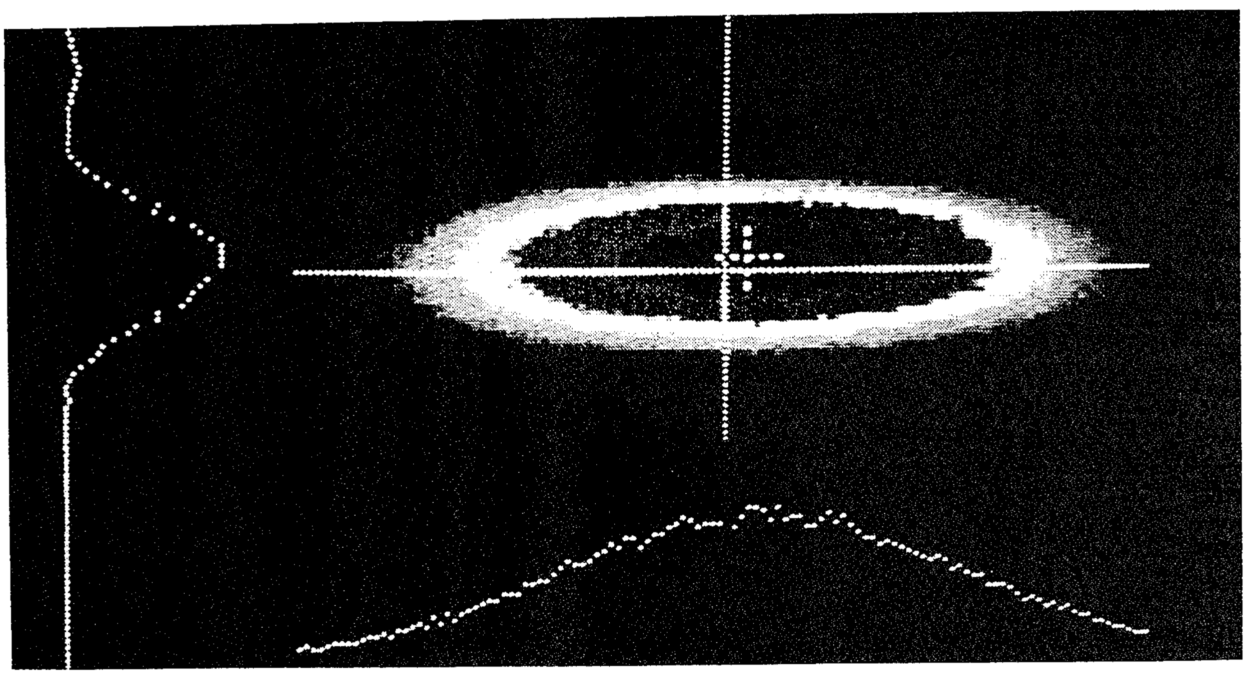

Figure 3. Far field intensity image of microlens collimated SDL-5410 diode laser. The plots on both sides of the figure represent the intensity profiles for the two orthogonal axes.

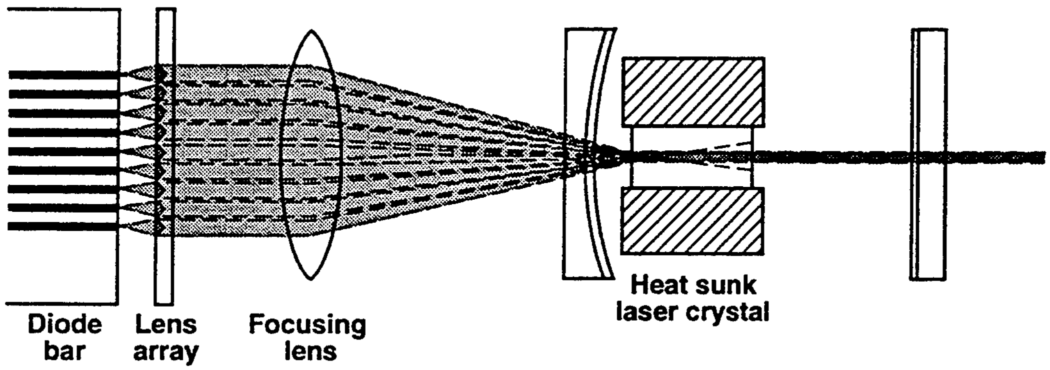

Figure 4. Diode bar plus microlens array configured to longitudinally pump a solid state laser.

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